The Bow, EnCana: Design, Monitoring, and Results of a Deep Excavation in Downtown Calgary

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The Bow office complex will become the new headquarters of EnCana Corporation, a leading Canadian oil and gas company. The shoring system, encompassing nearly two city blocks to a depth of 20.5 m, was required to support the surrounding utilities and buildings in downtown Calgary. Past excavations in the area experienced large amounts of rock movement, whose mechanics were poorly understood. The focus of this paper is the design process and construction results concerning rock movement and the effectiveness of the shoring structure.

A lack of information regarding the local in-situ stresses and shear band propagation in the bedrock led to research of case studies in the Calgary area and a peer review from local experts. From this, several geotechnical scenarios which accounted for varying residual rock stresses and the location and composition of weak rock layers suspected of causing shear band movement were analyzed using FLAC. Movement characteristics throughout construction were predicted that would identify the rock deformation mechanic.

A detailed monitoring program composed of precision monitoring targets, inclinometers, and extensometers was established to provide accuracy and redundancy in establishing the movement of the rock and excavation support structure. The results of the program were used to identify the rock deformation mechanics and further refine the FLAC analysis. To date, monitoring indicates that localized shear band effect is the leading cause of rock movement and is strongly correlated to excavation extent.

Introduction

EnCana Corporation, based in Calgary, Alberta is one of the largest independently owned energy companies in the world. EnCana is currently spread throughout five separate offices within downtown Calgary but will soon consolidate its employees and create a lasting impression upon the Calgary sky line with the addition of The Bow office tower. The Bow is located in the heart of downtown Calgary, with the Petro-Canada Centre to the west, the Telus office tower to the north, and Calgary's Light Rail Transit (LRT) line to the south. Spread over two city blocks, straddling 6th Avenue, the complex is split into two sections, including a 54 storey Bow office tower on the north block and a cultural centre to the south which incorporates the original brick façade of the York Hotel. The tower is designed to be ergonomic and energy efficient, with a fully enclosed atrium stretching up to the top of the building and trapping light and heat for the offices, with garden floors throughout the building.

The Bow project is currently the largest urban excavation in Canada, outside of Toronto. With a footprint of approximately 17,000 m^2, a shored face of 13,200 m^2 and a depth of 20.5 m, the excavation support system was required to overcome numerous challenges presented by the site's size, location, and geology. Over the span of the project, over 4700 m^3 of concrete were used, approximately 6400 m^2 of shotcrete were placed, and nearly 1600 anchors were installed. 6th Avenue, the division between the two sections, was demolished to allow for the construction of the six storeys of underground parking stretching across the entire site.

The site stratigraphy is composed of fill above 6 to 7 m of well graded gravels and cobbles over bedrock composed of layered weak mudstones, siltstones, and sandstones, with the predominant mudstone highly susceptible to weathering. A major design concern was the lack of information regarding the in-situ stresses of the bedrock and the location and effects of shear band propagation in weak rock layers. Extensive FLAC analysis of the design was supported by background research of case studies in the Calgary area combined with a peer review from local experts. Several geotechnical scenarios emerged which accounted for varying residual rock stresses and the location and composition of weak rock layers suspected of causing shear band movement.

To ensure the performance of the shoring wall, Peck's 'Observational Method' was employed with a detailed monitoring program. The monitoring program included 12 inclinometers, 8 extensometers, and precision target monitoring of the shoring wall and surrounding buildings. During the course of excavation and construction, the monitoring results were used to determine the global and section specific performance of the shoring system, re-evaluate the bedrock properties for more accurate FLAC analysis, and evaluate the properties, effects, and magnitudes of shear band propagation.

Geotechnique

AMEC Earth and Environmental performed geotechnical investigations at the site in 2005 and 2006. The ground surface at the 190 m long site is generally level, with elevations ranging between 1045.5 to 1046.3 m. The site consists of 0 to 0.5 m of fill over 5.5 to 7.0 m of well graded gravel. The gravels and cobbles are well rounded fluvial deposits from the glacial rivers in the area. Bedrock was encountered between elevations 1039 to 1041 m, with localized areas reaching 1035 to 1036 m. Groundwater is located in the soils and varies seasonally from 1 m to 3.5 m in depth above the rock surface. The bedrock consists of layered mudstone, siltstone, and sandstone the Porcupine Hills formation with nearly horizontal bedding. The siltstones and sandstones form indurated lenticular layers of varying thickness and extent throughout the majority mudstone. Formed as lacustrine deposits, the cementing agent of the mudstones and siltstones is clay, giving these formations a more soil like quality than the sandstone lenses. The mudstone varies from very weak to medium strength, with the siltstone and sandstone layers having medium to high strength. The mudstone is prone to rapid weathering with the addition of oxygen and water after excavation.

The mechanical properties of the bedrock formation are undocumented and poorly understood. The Porcupine Hills formation is known to exhibit large lateral in-situ stresses ($K_0 = 2.0$) as well as susceptibility to shear band propagation in weak layers of mudstone. The shear band phenomenon was suspected to have resulted in elevated lateral movements in the past at two nearby excavations.

The shear band effect is believed to be the result of a progressive failure along a thin layer of weak mudstone that results in excessive movement of the shoring wall. As the excavation progresses, the vertical stress dissipates and the larger horizontal stresses begin to adjust to the new conditions. Weak layers that exist at or near their ultimate strength at the in-situ stress level are subject to adjustment in the stress regime and the subsequent strain, causing the rock to exceed its peak strength and deform with lower residual strength. This would result in excess strain, most likely in the form of shearing in the rock. The excess strain is then propagated away from the face during the continued changes in stress by a weakened section of the affected mudstone causing successive failure along that layer. This weakened layer is referred to as the shear band, and the excess movement as the shear band effect.

Table 1 provides the engineering properties used for the design and analysis. Effort was made to explore the range of parameters suggested by the local Geotechnical review team. The parameters were checked against the conditions and range of movements observed at nearby Calgary deep excavations. Overall, the recommendations provided by the team were found to provide representative results when compared to the movements experienced at some Calgary deep excavation sites.

Description	Top Elevation m	Bulk Modulus MPa	Poisson's Ratio	Internal Angle Fric Deg	C' kPa	Unit Weight kN/m3	Dilat	Shear Modulus MPa
Soil cap	1046	36	0.33	28	25	21	0	13.6
Gravel soils	1043	73	0.33	36	0	20	2	27.8
Weathered Bedrock	1039	104	0.33	26	50	22	0	36
Up sound Bedrock	1037	112	0.27	40	100	22	0	67
Lwr sound bedrock	1032.5	133	.285	40	125	23	0	75
* Shear Band*		13.3	.285	5	0	23	0	2.5

Table 1. Soil engineering properties assumed for the final FLAC analysis.

For the modelling and analysis of the shear band effect a number of different localised models were used including: a soft plastic rock layer, possessing approximately 1/20th the strength and stiffness of the surrounding rock, and a weak non cohesive layer and interface slip elements.

Design Philosophy and Excavation Support Geometry

The Tender design consisted of soldier pile and lagging with areas adjacent to structures used full length caisson wall. This design did not address the concerns of soil loss in the gravels, excessive groundwater ingress into the excavation, weathering of the mudstone, or with risk associated from movements driven by rock mechanics.

The successful alternative design incorporates a continuous caisson wall installed 2 m into the sound rock with an anchored shotcrete wall beneath in the excavated bedrock. This design eliminates typical soil loss in the gravels, aides in controlling groundwater ingress, prevents the weathering of the bedrock, and addressed the movements caused by rock strain. The design geometry is provided in Figures 1 through 3. The caisson wall consists of interlocking 880 mm diameter drilled, cased holes with W460 x 68 kg soldier piles set between 2 fillers. All concrete had a minimum strength of 5 MPa. The filler piles extend 2 m into rock with a single filler per bay extending 4 m into sound dry rock, which improves the caisson wall to shotcrete transition. The toe of each pile is constructed of fortified caisson mix, where a minimum of three 40 kg bags of concrete are added and mixed into the bottom 2 m (anticipated 15 MPa).

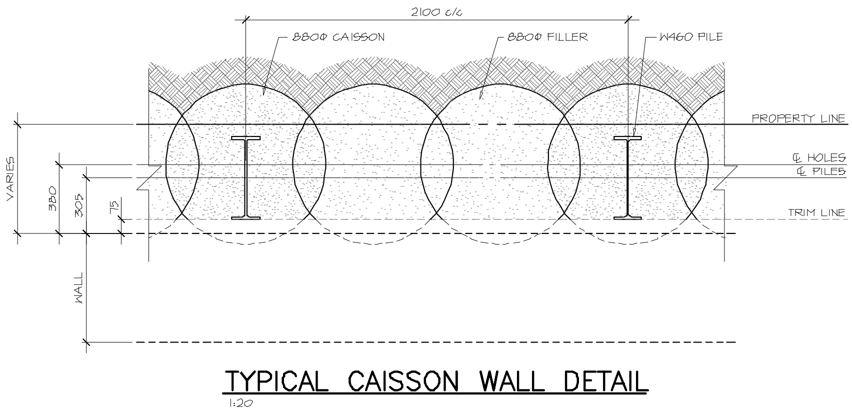

Figure 1. Typical plan detail showing caisson wall layout.

The shotcrete wall was constructed to act as a weatherproofing agent against deterioration of the mudstone bedrock. The excavation procedure for the shotcrete wall was carefully controlled with a strict double benching procedure. The rate and staging of the berm removal was controlled by the shoring contractor such that all shotcrete was prepared and placed within 48 hours of exposure of the rock to the elements. The shoring contractor excavated the final 150 mm of rock using a concrete wheel abrator mounted on an excavator, producing a uniform, virgin rock condition prior to shotcrete application. Wick drains were placed against the rock face to train rock borne water from behind the shotcrete face into the excavation to prevent deterioration of the mudstone bedrock.

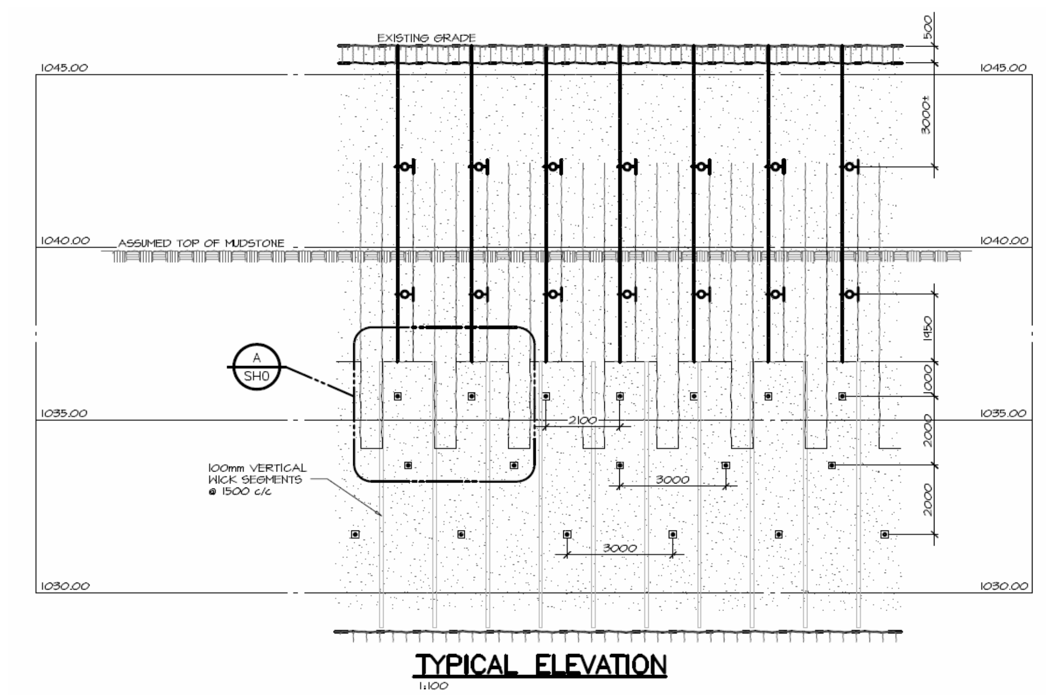

Figure 2. Typical elevation for excavation support.

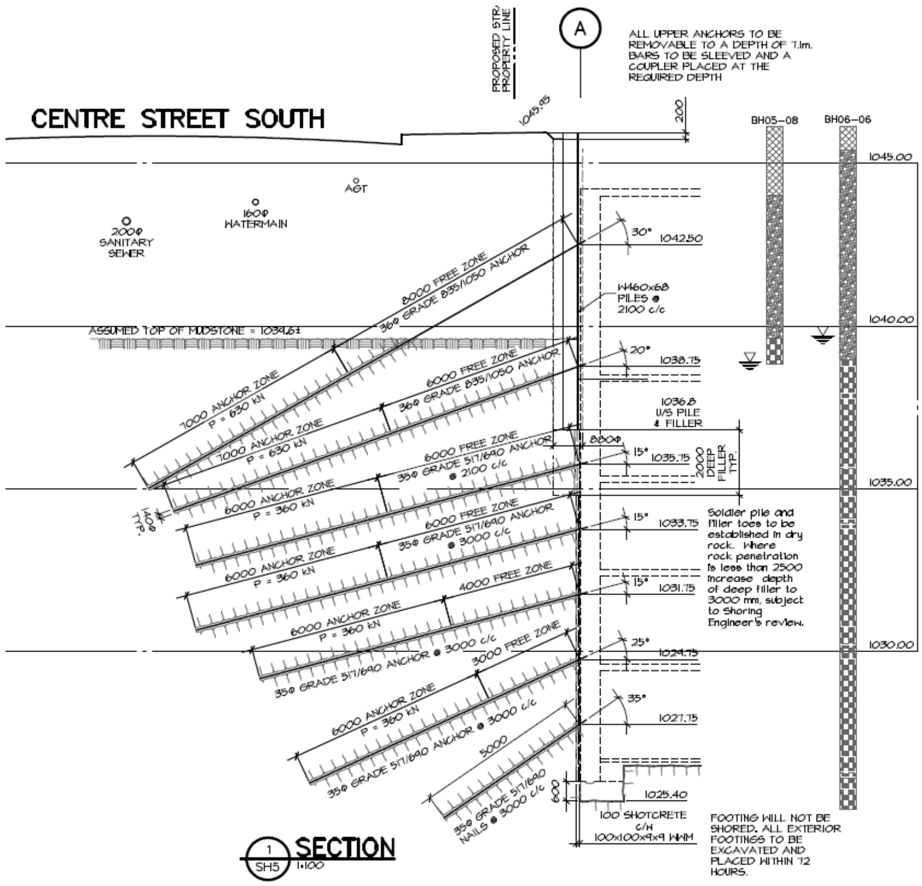

Figure 3. Typical section for excavation support, 20.5 m depth.

Modeling

The proposed excavation support system was analysed using Two-dimensional Fast Lagrangian Analytical Method (FLAC). The method has been used for geotechnical and mining engineering problems for over 15 years and has been well documented in literature. The 2D FLAC grid as modeled in the analysis is 105 m wide and 60 m in height with 13,700 discrete elements numbering 137 across and 100 high. The section modeled represents the typical geometry as provided in Isherwood Drawings with a depth of 20.5 m. The grid is not symmetrical and depicts the final geometry to a distance of 50 m towards the centre of the excavation.

In order to better understand the rock properties, an extensive analytical study was completed using case studies of excavation and shoring in the Calgary area and FLAC analysis. This was combined with a peer review session to help clarify the known processes and identify areas that required additional work. The case studies focused on excavations within the Porcupine Hills formation, and included jobs such as the James Short Parkade, City Parkade, and Banker's Hall in Calgary, and the Edmonton Convention Centre in Edmonton, Alberta. The results from these projects were analyzed in FLAC, with the required rock properties being back calculated. Local literature and expertise supported two mechanisms for excavation support movement in Calgary: elevated in-situ lateral soil stress condition (assuming a K_o of 2.0) and 'shear band effect' where localised progressive failure of a weathered mudstone layer propagated movements. Parametric studies were conducted under a variety of assumed soil parameters, in-situ lateral stress conditions and weak layered rock conditions (shear band conditions at depth).

The predicted loads and movements for the proposed excavation support are highly dependent upon the assumptions made regarding the integrity of the bedrock (shear band effects) and the residual lateral load within the bedrock. An extensive parametric study revealed that predicted movements increase substantially with various combinations of weak rock layers and lateral rock stresses. The caisson wall structural system is affected little by the changes in the assumed rock behaviour. The shotcrete wall is expected to perform within the design envelope despite changes in the assumed rock behaviour. However, substantial changes in rock anchor loading and wall movement are witnessed with the programmed changes in the rock behaviour. The most notable outcome of the analysis was the resulting shift in emphases from the in-situ lateral soil stress regime to the shear band effect as the major cause of lateral movement.

In keeping with the Observational Method, FLAC analysis was used to predict movements of the shoring and neighbouring soils and structures. The progression of predicted wall movements with excavation is dependent upon the mechanism of the driving force / rock integrity. Lateral stresses in weak rock promote a progressive movement deformation profile. Shear band effects produce more sudden movements of the wall face as a whole, as the excavation level nears the rock surface the shear band begins to reveal itself and manifests as large movements within a plane of the rock mass. Thus the characteristics of the progression of movement as the excavation is developed influence the interpretation and reaction to increased rock movements. Figure 4 provides the FLAC analysis performed for a deep seated shear band mechanism at a depth of 5 m below the final excavation level. Note the movements at the shear band are on the order of 30 mm and the total peak face movement is predicted at 45 mm.

The excavation support designers published a design prediction prior to the commencement of the project that provided projections of excavation face movements for baseline, shear band and $K_0 = 2.0$ scenarios. In keeping with the Observational Method, alert and action thresholds were also provided for each excavation stage. Based upon the characteristics and magnitude of the rock movements observed at the face additional analysis or remediative action would be invoked to control the excavation performance.

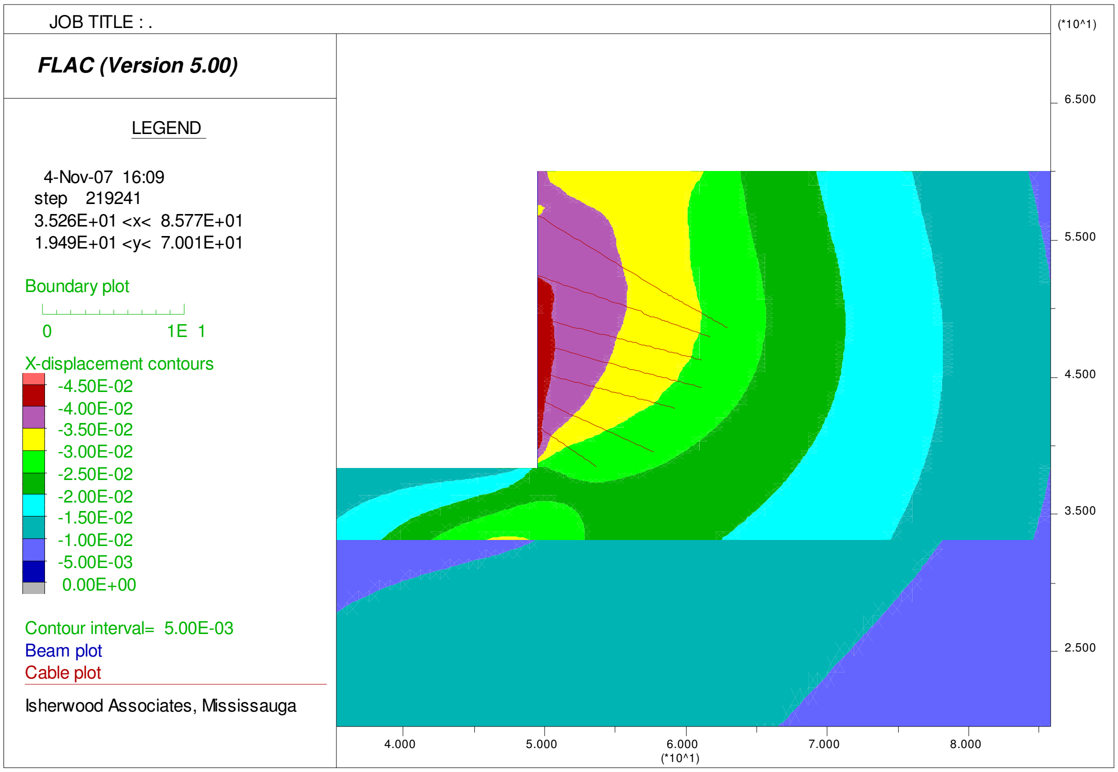

Figure 4. FLAC analysis for deep seated shear band effect 5 m below final excavation depth.

Monitoring Program

The extensive monitoring program implemented at The Bow project involved a combination of 12 inclinometers, 8 extensometers, and precision target monitoring of the shoring wall and neighbouring structures. The monitoring program for The Bow's excavation support system was designed to ensure the full and redundant observation of the shoring wall and rock movement. Monitoring instruments were clustered at locations chosen to best reflect the behaviour of the wall face at critical sections of the excavation.

Precision target survey was conducted at desired locations on the shoring and surrounding structures with accuracy to within 4 mm. At the Bow, survey targets were chosen for the shoring wall, at the top and bottom of each pile and at lower anchor rows. The top and bottom of pile targets provided early indication of the caisson wall behaviour and confirmed movement readings of the other instruments. Targets on the shoring wall were reported weekly, while targets on the surrounding structures were reported monthly.

Inclinometers were read weekly to determine the horizontal movement profile in the vertical plane of the shoring face, both in the wall and well into the rock below. In general, the inclinometers were installed to a depth of 10 m below the final excavation to ensure any deep seated movements were captured.

In conjunction with the precision targets and inclinometers, extensometers were also installed at 8 locations across the site. The 25 m SMART cable extensometers are composed of 6 LVDTs that measure the relative movement of the rock mass with respect to the excavation face. The purpose of these instruments was to determine the distribution and magnitude of rock movement beyond the face of excavation. Placed just below the bedrock surface, the extensometers were installed at 7 degrees to horizontal and encased in a special grout mix that would achieve strengths as close to the natural rock as possible. The location and orientation of the extensometers ensured that the maximum amount of rock expansion was recorded, while the weak grout mix prevented the extensometer from creating a stiff column within the rock and giving falsely low readings. Combined with the target monitoring and inclinometer readings, the extensometers presented an excellent profile of the rock expansion beyond the shoring wall.

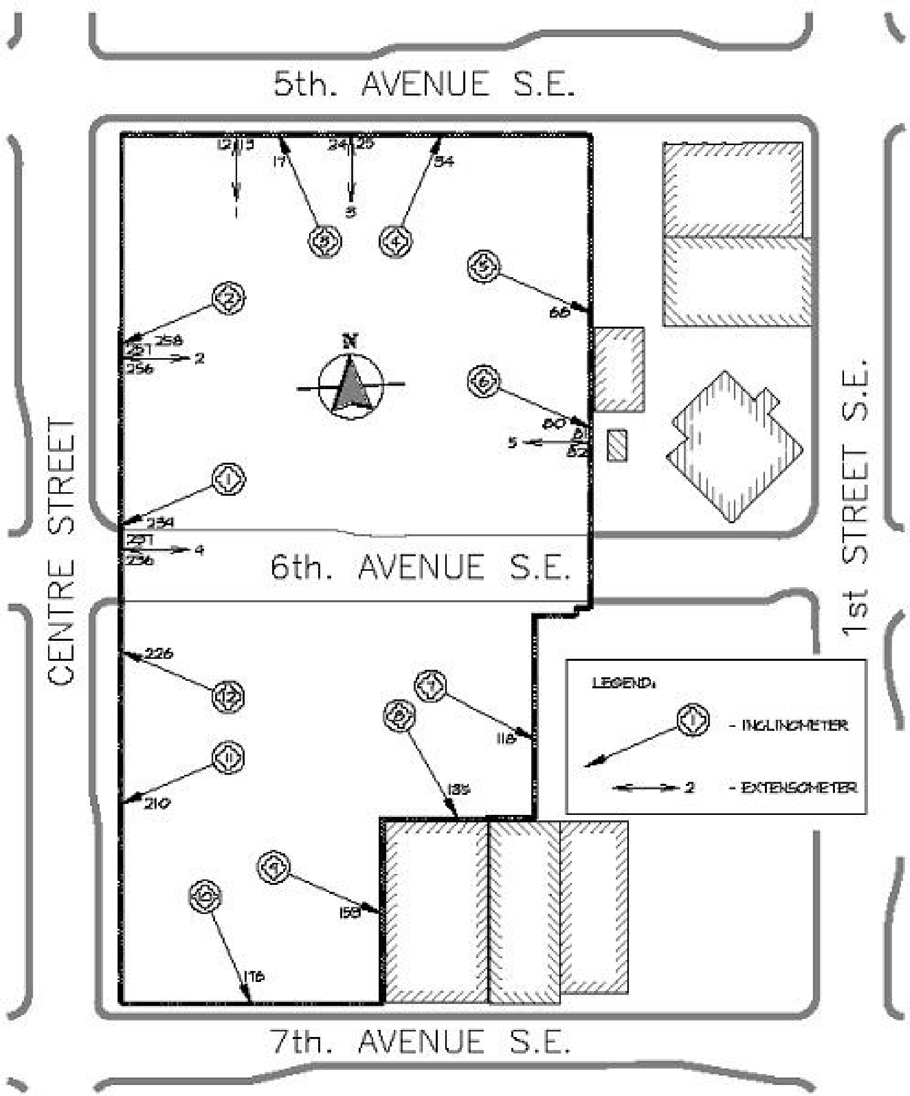

Figure 5. Monitoring instrument locations

The full monitoring program integrated the instruments to determine, with redundancy, the full extent of movement and behaviour of the shoring wall, soil and rock mass. The rates and magnitudes of movement were compared on a weekly basis with all three types of instruments to determine the validity of the results. The monitoring layout, showing the locations of inclinometers and extensometers, is shown in Figure 5.

Monitoring Results

The monitoring program was a major success at The Bow. It was used with high efficiency to accommodate Observational Method during construction, but most importantly, it defined the bedrock and shear band phenomena's properties, behaviour, and movement extents.

The shear band effect was observed to occur at several locations during excavation including the north wall and at the 1st Canadian Legion, in Inclinometers #4 and #8, respectively. Inclinometer reports, verified by the precision monitoring, indicated that the shear band movement was the major driving mechanism for large horizontal deformations of the rock. This was observed along the north wall and the northwest corner of site, where the total movement ranged from 45 to 70 mm into site. Over half of the movement observed is derived from the shear band, as shown in Figures 6 and 7. The figures show a compilation of the readings over the duration of the project with Inclinometer #4 showing shear band and Inclinometer #5 showing a typical baseline or non shearing section. This confirmed the hypothesis of the design team that reported large movements at neighbouring excavations in Calgary were the result of shear band effect and not elevated K_0.

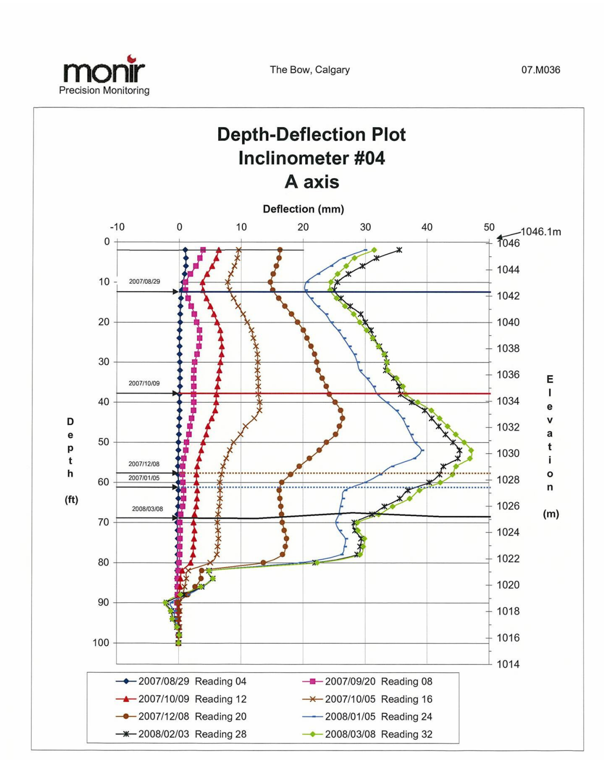

Figure 6. Inclinometer #4 showing shear band at elevation 1021m.

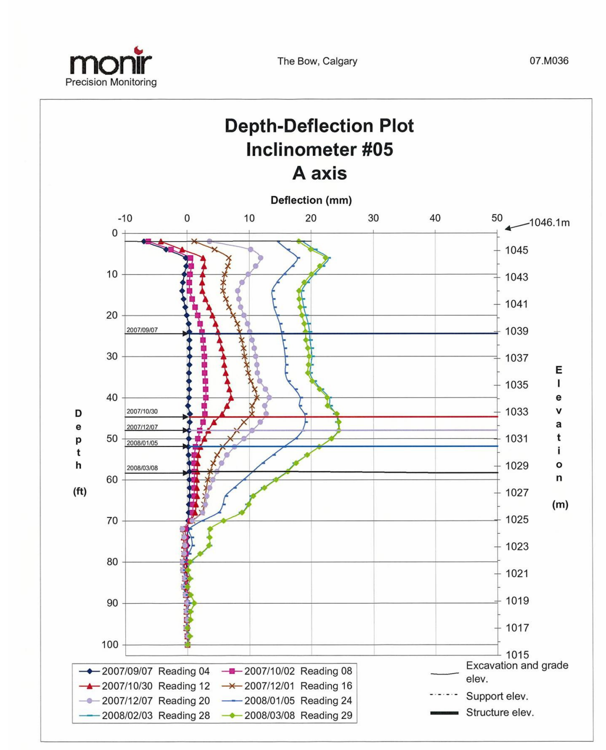

Figure 7. Inclinometer #5 East wall.

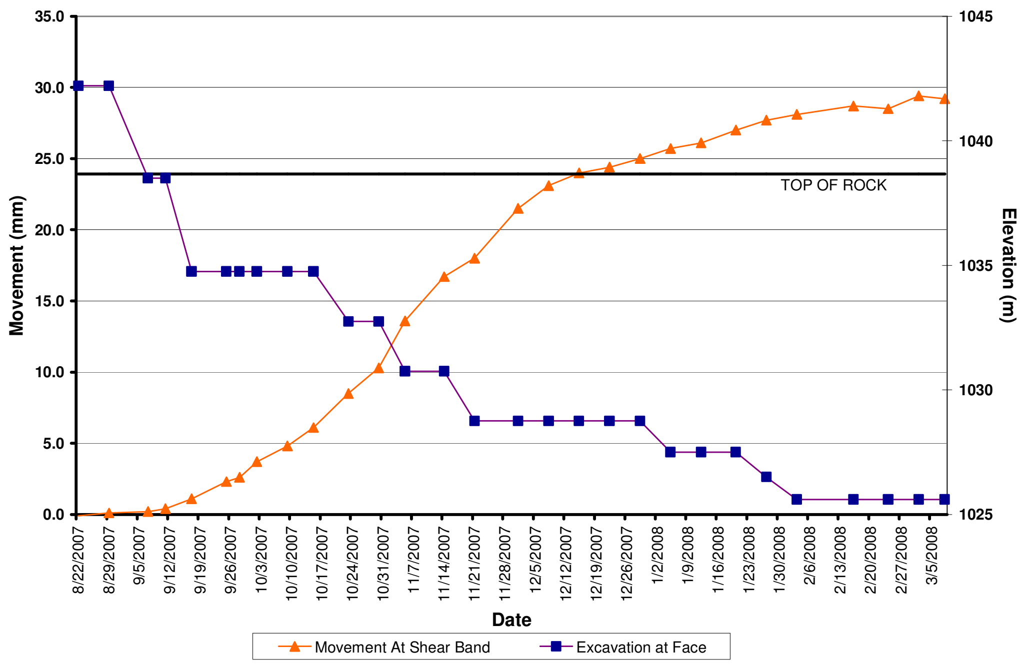

Figure 8. Shear band (triangle) and excavation elevation (box) over time.

The results of Inclinometer #4 indicated a clear shear band forming at elevation 1021 m. The net movements over time at this elevation were then compared to the progressing excavation elevation, as shown in Figure 8. The graph indicates that the shear band at the north face began forming shortly after excavation to the bedrock occurred, and that movement rates accelerated with each bench development and dissipated between excavation events. A remarkable observation is that despite occurring up to 17 m below the rock surface, the shear band began forming shortly after excavation began. In addition, similarity in the deflection shape between Inclinometer #4 above the shear band and Inclinometer #5 indicates that the stress regime above the shear band is not affected by the propagation of the band.

Extensometer plots at the north wall assist in determining the extent of the shear band effect beyond the excavation face. Results from Extensometer #1 are shown in Figure 9, below. The readings indicate that movement is occurring past the reach of the extensometer, as shown by the non-zero slope of the readings at 25 m. Total movement at the face before installation of the extensometer can be determined by comparing and adding the precision survey and inclinometer readings at the time of the installation of the extensometer and throughout the duration of the project. Once the difference in net movement has been determined, the extensometer readings can be adjusted to accurately reflect the total horizontal strain in the rock mass. From Figure 10, we see that all three of the monitoring instruments show the same movement patterns at the elevation of the extensometer. The adjusted extensometer readings are shown in Figure 11, reflecting the net movement of the extensometer and the total extent of the rock expansion due to shear band effects. This Figure indicates that shear bands cause uniform expansion in the rock well past 25 m from the shoring face.

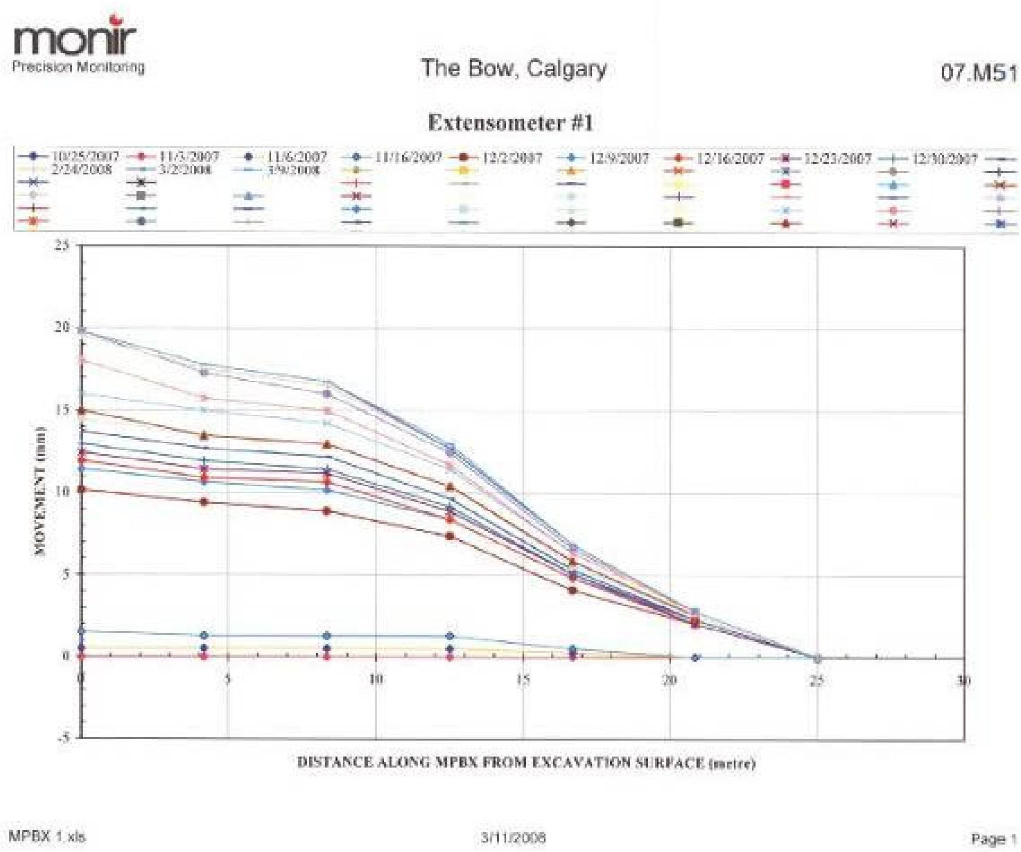

Figure 9. Extensometer #1 showing movement beyond face of shoring

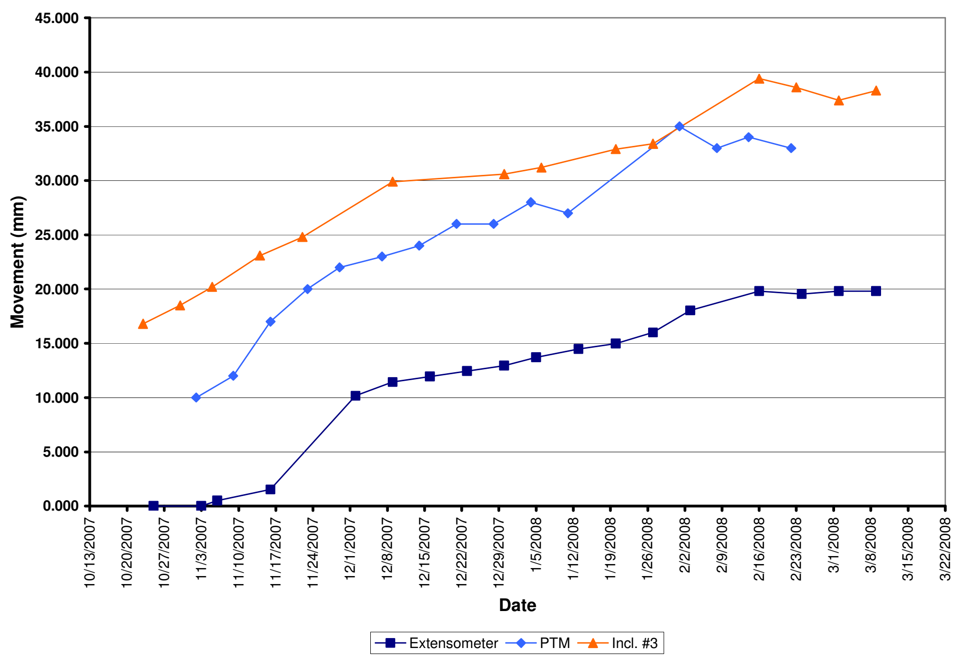

Figure 10. Comparison of net movements of shoring face at Extensometer #1

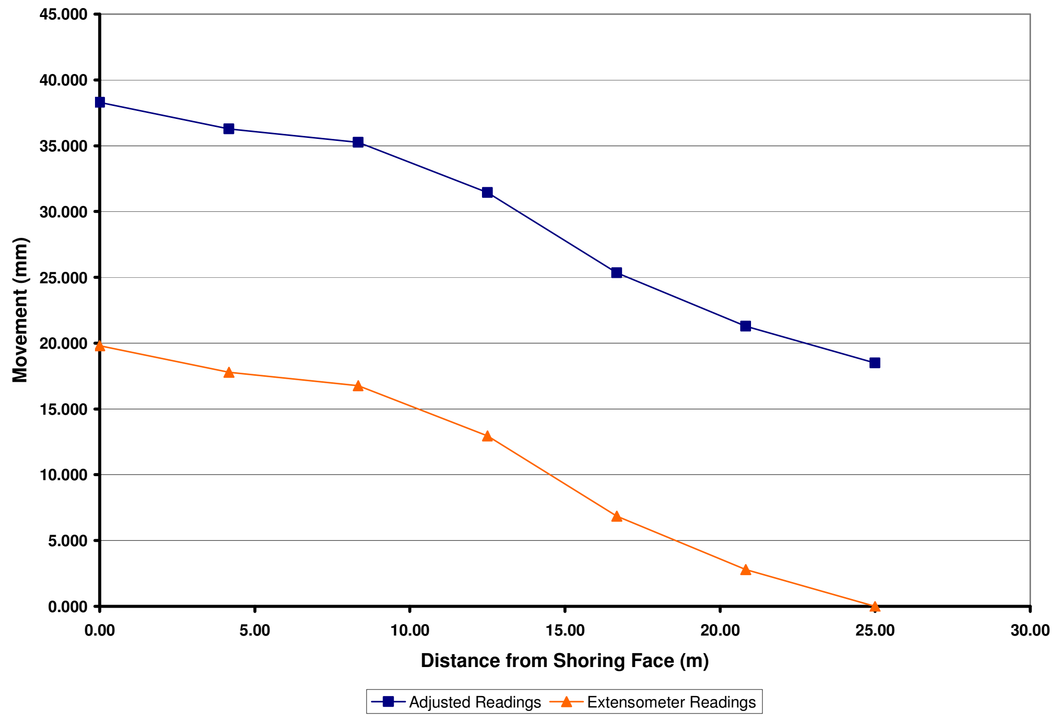

Figure 11. Adjusted movements for Extensometer #1

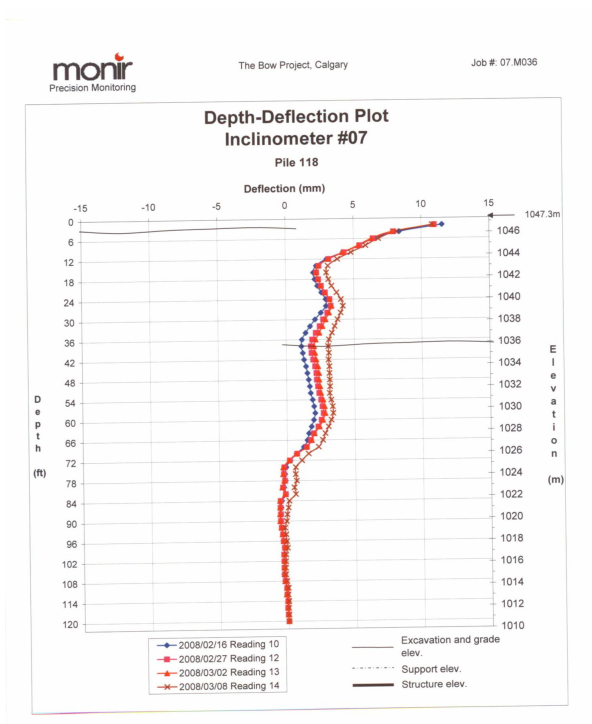

Figure 12. Inclinometer #7 East wall

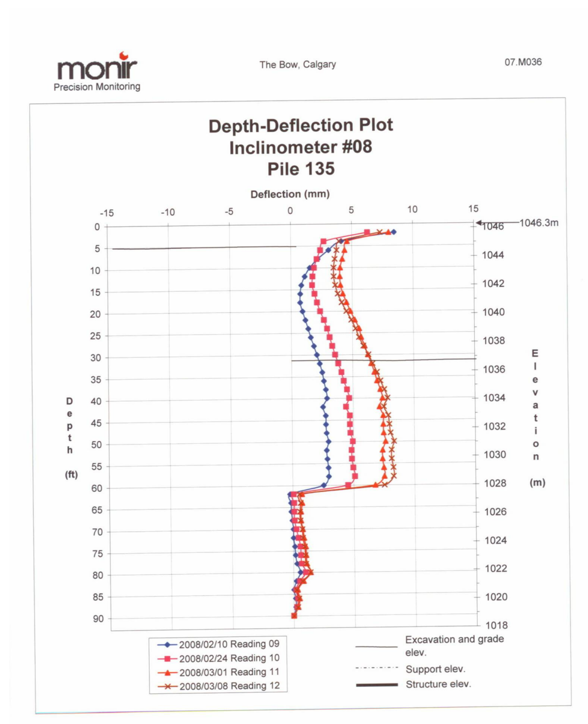

Figure 13. Inclinometer #8 South wall showing shear band at elevation 1027 m

The shear band also appears to be highly directional, as seen with the results of Inclinometers #7 and #8, shown in Figures 12 and 13, respectively. This area is located in a corner beside the Andrew Davison to the east (Inclinometer #7), and the 1st Canadian Legion to the south (Inclinometer #8). As the excavation progressed in this area, Inclinometer #8 began showing a shear band phenomenon occurring, whereas Inclinometer #7 showed normal rock expansion behaviour. Despite being less than 30 m apart, and influenced by the same excavation, the shear band was only observed in a north-south direction as shown in the results of Inclinometer #8.

Rock expansion characteristics in the Porcupine Formation were also observed through the inclinometers and extensometers. The east wall of the shoring system did not experience shear band propagation, allowing the monitoring to record the relaxation in the rock. As seen in Figure 7, of the A axis of Inclinometer #5, the rock expansion occurred at a steady pace during excavation. In addition, Extensometer #5 (Figure 14) shows movement in the rock dissipating at approximately 17 m from the face. Using this information, additional FLAC analysis was completed to back-calculate more accurate bedrock properties for further modeling and prediction.

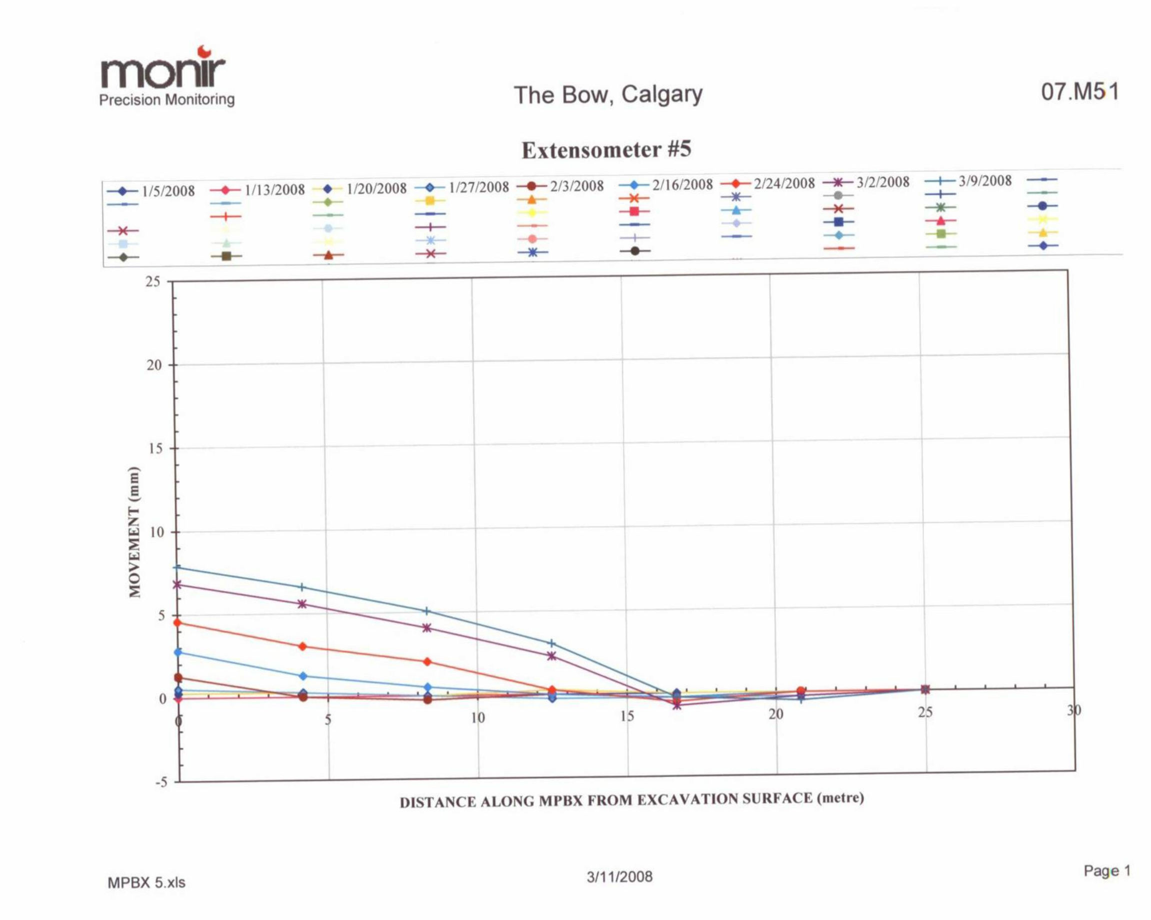

Figure 14. Extensometer #5

Conclusions

Given the results of the monitoring program, the design for The Bow site accurately predicted the practical and geotechnical issues to ensure a proper excavation support system. The detailed background research and intensive FLAC predictions correctly identified the movement characteristics of the soil and rock mass. The effectiveness of the caisson wall over shotcrete effectively negated the issues of soil loss, groundwater ingress, and bedrock degradation.

The monitoring program was effective in supporting the Observational Method of design, as well as identifying and measuring the shear band phenomenon. From the results of the program, the shear band effect has been identified as being the driving factor for large horizontal deformations in deep, downtown Calgary excavations. Additionally, the shear band phenomenon has been correlated to excavation extent, and shown to be localized, directionally dependant and appears dissipative over short periods of time (within the schedule of the deep excavation).

The extensive monitoring correlated to FLAC analysis and re-analysis throughout the excavation program allowed the design team and owners to react to very large observed shoring movements in a sensible, safe and economical manner that did not impact the construction schedule. In the absence of a correlated design and an analytical approach based upon an effective monitoring program, the client's reaction to the large movements observed could have been unnecessary, litigative and wasteful.